DESIGN, FABRICATION AND CHARACTERIZATION OF AN INTEGRATED MICRO HEAT PIPE

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ABSTRACT

The design, fabrication and characterization of an integrated microsystem consisting of micro heat pipes, a micro heater, temperature and capacitive microsensors are presented. CMOS-compatible micromachining techniques are utilized to fabricate the micro heat pipe device capped by a nitride layer. In order to allow clear visualizations of the flow patterns during operation, the process has been modified using a glass wafer to cap the heat pipes. Temperature distributions along the micro heat pipes have been measured using the microsensors located next to the heat pipes. The capacitive microsensors have been used to measure the void-fraction, taking advantage of the large difference between the dielectric constants of the liquid and vapor phases.

INTRODUCTION

As the number of components in VLSI devices continues to grow, it becomes more difficult to remove the heat generated by electronic components. Micro heat pipes are powerful cooling devices for reducing the operating temperature. The effective thermal conductivity of the region occupied by micro heat pipes was estimated to be about ten times that of the silicon substrate, while the maximum surface temperatures were reduced by 20% [1]. Furthermore, for non-steady state thermal performance, micro heat pipes in silicon can reduce the thermal time constant by more than 30% [2].

Although micro heat pipes have attracted considerable attention, integration of such a system utilizing CMOS compatible standard micromachining techniques has never been reported. The most popular cross-section for heat pipe is the triangle, which is easily obtained in orientation-dependent etch of Si. The difficulty lies in the technique to cover the pipes. Mallik et al. suggested fabricating triangular micro heat pipes by vapor deposition [3]. However, the fabrication of a complete micro heat pipe system has not been realized. In this work, a wafer bond and etch back technology is utilized, in which the triangular grooves are capped by a nitride membrane. This will then allow integration of any electrical or mechanical devices using standard CMOS-compatible processes [4]. For experiments, though, a glass cover is preferable for studying the flow patterns within the heat pipes [5,6]. Besides, the thermal conductivity of micro heat pipe is sensitive to the amount of water content in the pipe [7]. Hence, the void-fraction is an important parameter to analyze the two-phase flows in micro heat pipes. Capacitance sensors [8,9] can be used to measure the void fraction in two-phase flows. In this work, capacitive microsensors are integrated along the heat pipes to provide this crucial information of the vapor/water content.

DEVICE DESIGN AND FABRICATION

An integrated microsystem comprising a micro-channel array, a local heater, temperature and capacitance microsensors is designed to operate as a micro heat pipe system. In a fully CMOS compatible process, triangular grooves are etched in a Si wafer using TMAH, and the grooves are capped using wafer bond and etch back technology. A low-stress silicon nitride film is deposited on another Si wafer. Fusion bonding is then utilized to bond the two wafers with the nitride film at the interface. Next, the handling wafer is dissolved in TMAH, while the device wafer with the groove is protected. The etching stops on the nitride film, resulting in grooves capped by the nitride layer as demonstrated in Figure 1. This allows the integration of other devices using CMOS technology on top of the processed wafer.

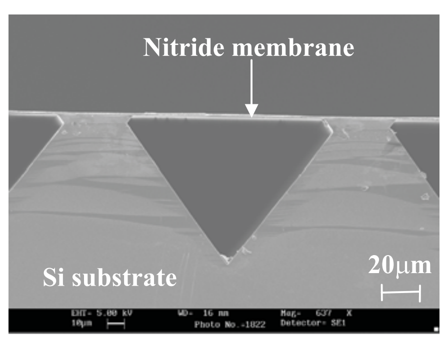

Figure 1:A SEM picture showing the triangular cross section of a groove capped by a nitride membrane.

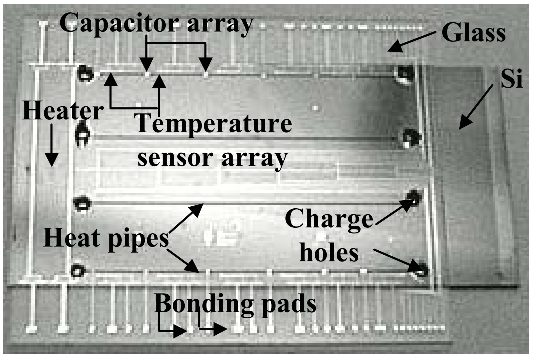

Figure 2: A picture of a fabricated device showing all the bondig pads on the glass side.

The transparency of the nitride film is not as good as glass. Therefore, in order to enhance the quality of flow visualizations in the experiments, a glass wafer is used to cap the grooves as shown in Figure 2. An aluminum layer was first sputtered and patterned on the glass wafer for both metal interconnects and capacitor top electrodes. Holes were next drilled through the glass wafer, two holes for each groove, to facilitate charging of the heat pipes with the working fluid. Then, the glass wafer was anodically bonded to the silicon wafer with the grooves.

The heater was placed on one edge of the device to serve as a heat source. The other edge was designed to allow contacts with a cold heat sink for heat dissipation. The heater was formed in the silicon substrate to minimize the heat loss to the surrounding. Both the heater and the temperature microsensors were fabricated by selective boron implantation in N-wells, which were defined by phosphorus implantation. The temperature sensors, each about 6 by 4μm^2 in area, were located next to the heat pipe as shown in Figure 3a. The bottom electrode for the capacitors was created by doping the grooves prior to bonding. Hence, the capacitance between the top electrode, shown in Figure 3b, and the doped substrate should be a function of the dielectric constant of the fluid between the two electrodes. The sensor can then be used for measuring the local void fraction, on which the dielectric constant depends.

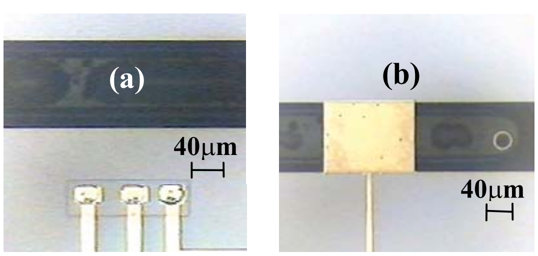

Figure 3: Close-up pictures of (a) a temperature sensor, and (b) the upper electrode of a capacitive sensor (the lower electrode is the doped Si substrate).

Schematic cross-sections of the major fabrication steps are shown in Fig. 4. The fabrication began with 0.3μm thermal oxide growth on a (100), p-type Si wafer, Figure 4a. N-wells were formed by phosphorus implantation, followed by activation and drive-in. Boron was selectively implanted within the N-wells to fabricate the heater and the temperature microsensors, Figure 4b. After the deposition of a 0.5μm-thick LTO layer, V-grooves were etched using TMAH to create the triangular-shaped pipes. Boron was diffused into the grooves and the wafer backside to form the capacitor bottom electrode and, in the process, growing a 0.1μm-thick thermal oxide for electrical insulation, Figure 4c. In the CMOS process, wafer bond and etch back would be performed at this stage to cap the grooves. In the present experiment, contact holes were opened for the heater and temperature sensors. This was followed by aluminum sputtering and patterning for the interconnections, Figure 4d. On the Pyrex 7740 glass wafer cap, Al was sputtered and patterned for both the interconnections and the capacitor top electrodes, Figure 4b. Subsequently, charging holes for the heat pipes were drilled through the glass, Figure 4c. Finally, the silicon and glass wafers were aligned and anodically bonded die-by-die to complete the fabrication process, Figure 4d.

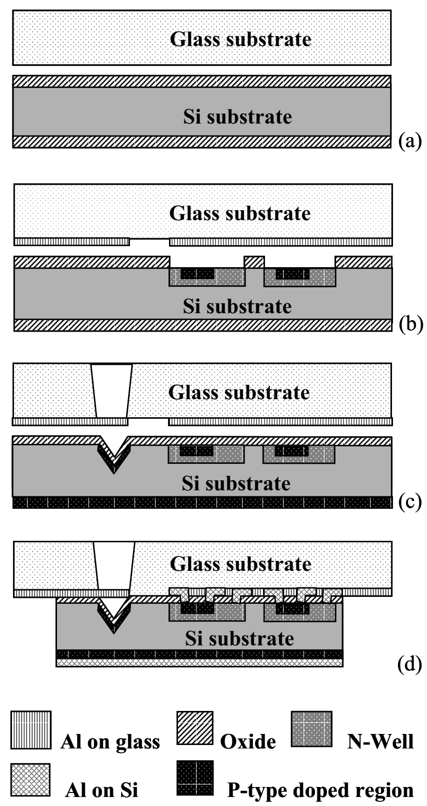

Figure 4: A device cross-section summarizing the major fabrication steps.

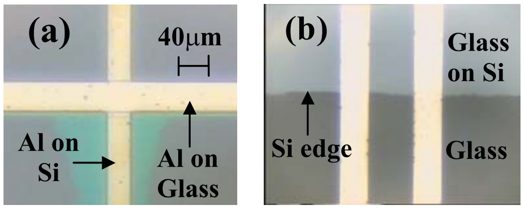

Figure 5: Close-up pictures of (a) the intersection between the metal lines, and (b) the continuous metal lines on the glass side after bonding.

In order to minimize the parasitic capacitance of the sensors, all the bond pads were formed on the glass side. The metal patterns on the Si and glass wafers were designed to cross each other after the anodic bonding, Figure 5a, to transfer all the electronic signals to the metal lines on the glass. The glass die was wider than the silicon die to minimize the overlap between the bonding pads and the silicon. The integrity of the metal lines was kept through the interface between the glass and the silicon edge as demonstrated in Figure 5b.

EXPERIMENTAL SET-UP

The micro heat pipes were charged with DI water through the charging holes, which were later sealed. An adjustable voltage source controlled the heat generated by the heater at one end of the device. The other end was connected to a constant temperature sink kept at 16°C to remove the heat from the microdevice. The output signals of the temperature and capacitive microsenors were recorded using a computerized data acquisition system and digital LCR meter, respectively. The evolving flow patterns in the micro heat pipes during operation were recorded using a VCR through a CCD camera mounted on a microscope.

RESULTS AND DISCUSSION

Device characterization started with the calibration of the temperature sensors. The relative resistance change increases almost linearly with the temperature change, as depicted in Figure 6, resulting in a positive TCR of about 0.15%/°C.

Calibration of the capacitive sensor is trickier as it depends on the air/water volume ratio between the electrodes, which is difficult to control. However, the two extreme points of 100% air or water are clear. The capacitance increases with water content in the mixture. Since the dielectric constant of vapor is almost the same as that of air, the capacitive sensor can be used to measure phase content. The relative capacitance change decreases almost linearly with the void fraction as shown in Figure 7.

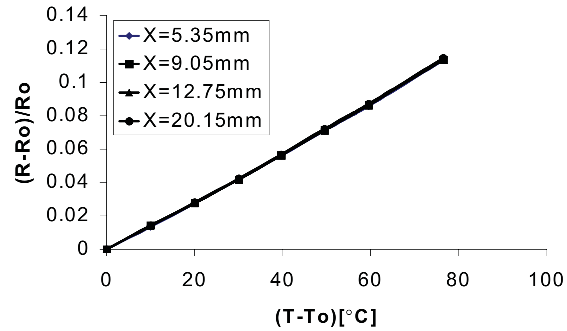

Figure 6: Calibration curves of the temperature sensors resistance change as a function of the temperature change.

Following the calibration procedures, the heat pipes are charged with DI water and then sealed to allow testing. Flow visualizations verify the development of the three distinct zones in the micro heat pipes: evaporator, adiabatic and condenser, shown in Figure 8. The evaporator region is next to the heater, Figure 8a, having the highest temperature. A portion of the input power is converted into latent heat of phase change of the working fluid in the evaporator. Thus, the highest void fraction is observed in this region. The heat flows from the evaporator to the condenser through the adiabatic region. In this region, Figure 8b, an annular-like flow is developed. Liquid flows towards the evaporator due to the capillary force at the corners, while vapor at the core flows towards the condenser due to pressure gradient. The vapor is condensed back to liquid at the other end of the heat pipe, Figure 8c; thus, transferring the latent heat of phase-change from vapor to liquid to the cold sink. Since the micro heat pipe is fabricated by bonding glass to silicon wafer, most of the heat is conducted through the silicon, leaving the glass cover relatively colder. Therefore, a fraction of the vapor condenses on the ceiling to form liquid film or droplets as shown in Figure 8.

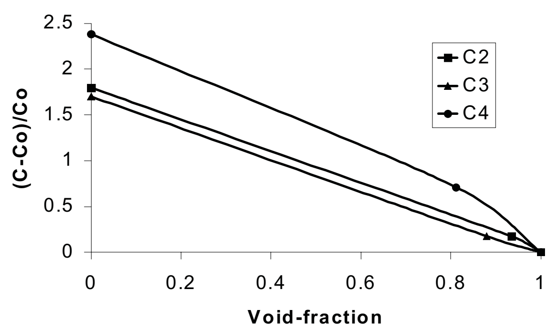

Figure 7: Calibration curves of the capacitive sensors relative capacitance change as a function of the void-fraction in V-groove.

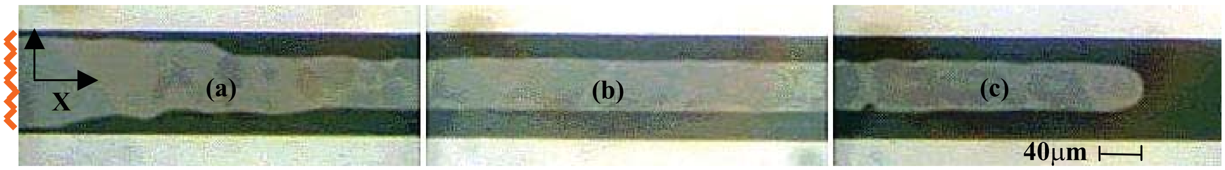

Figure 8: The flow pattern at the (a) evaporator, (b) adiabatic, and (c) condenser region of the micro heat pipe with the heater located at the left edge of the heat pipe.

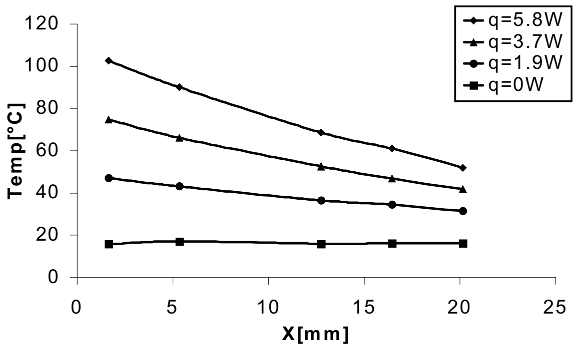

Figure 9: Temperature distribution along the micro heat pipe for different input-power level.

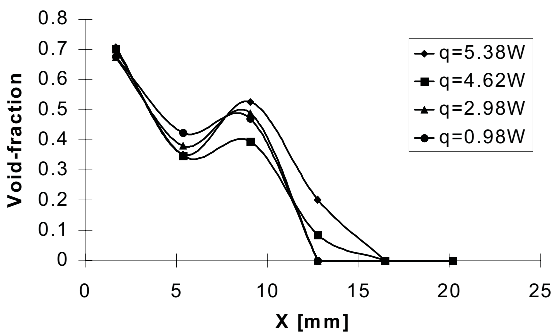

Figure 10: Void-fraction distribution measurements due to the vapour/water mixture gradient.

Temperature distribution measurements along the heat pipe for different input power level are summarized in Figure 9. The temperature decreases almost linearly with the distance from the heater, and the negative temperature gradient increases as the input power increases. When the input power level is low, no evaporation of the liquid water takes place. Hence, the water inside the micro heat pipe simply conducts the heat with no phase change. However, at high input power level, some of the energy is converted into latent heat for phase change of the working fluid at the evaporator.

The mixture void-fraction measurements using the capacitive sensors are plotted in Figure 10. The transition from vapor to liquid zone via the adiabatic region is clear. The void fraction in the evaporator is high, about 0.7, while in the condenser region it is about zero. The void fraction does not drop smoothly since, at some locations, the vapor re-condenses on the ceiling locally increasing the water content.

CONCLUSION

A micro heat pipe system has been fabricated using a CMOS-compatible process. Glass `bonding has been utilized together with integrated temperature and capacitive microsensors to study the details of the two-phase flow in the heat pipes during operation. The bonding pads of the sensors have been placed on the glass substrate to minimize the parasitic capacitance. Visualizations of the evaporator, adiabatic and condenser regions confirm the proper operation of the micro heat pipe device. Measured temperature distributions are nearly linear along the heat pipes. The void-fraction measured by the capacitive sensors are consistent with the flow visualizations, indicate transition from vapor to liquid phase as the distance from the heater increases.

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